An Introduction to Forecasting Contrails

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Introduction

An exhaust contrail or condensation trail is a cirrus-like trail of condensed vapor that is produced by jet aircraft flying at high altitudes in clear, cold, humid air. Contrails are generated at altitudes high enough for water droplets to freeze in a matter of seconds and not quickly evaporate (typically where the temperatures are below –38 degrees Celsius).

Contrails can form by the addition of water vapor to the air from the jet engine exhaust itself. In this case, there must be sufficient mixing of the hot exhaust gases with the cold air of the atmosphere to produce a state of saturation. Even the tiny nuclei released in the exhaust fumes may be sufficient to generate ice crystals, and hence, contrails.

Contrails may also form by a cooling process. The reduced pressure produced by air flowing over the wing causes the air to cool. This cooling may supersaturate the air, producing an aerodynamic contrail. This type of trail usually disappears quickly in the turbulent wake of the aircraft. [Ahren, 1991]

Contrails spread apart and evaporate with time, but how quickly this occurs depends upon a couple of factors. If the air in which the cloud forms has a low relative humidity, the cloud particles will rapidly evaporate. If the relative humidity is high, however, contrails may persist for many hours. However, even in air of higher relative humidity, upper level winds can spread contrails apart, forming a horizontal sheet-like cloud.

Impact on Military Operations

Contrails can influence weather and climate by modifying the cloud cover. Also, contrails can have a military and strategic significance in that they reveal the presence and location of high-level aircraft that would normally be invisible to the naked eye. The enduring memory of many who witnessed the Battle of Britain, during the Second World War, is the criss-crossing spider's web of contrails that occurred day after day, high above England, as the Luftwaffe and the Royal Air Force engaged in combat in the upper levels of the troposphere. [Burroughs, 1996] Also in WWII, high-altitude bomber formations, especially over Europe, were easily located by the presence of their contrails. In some cases, German fighters would merely have to locate a contrail and follow it directly to an invading aircraft. As the war progressed, camouflage painting of American bombers and fighters was discontinued because it saved weight and did little to conceal an aircraft producing a long contrail. Today, the problem of contrail formation is even more important since stealth aircraft have become operational. Stealth bombers and fighters are just as easy to detect as conventional aircraft when they produce contrails, even at night. [Asbury, 1997]

Accurate forecast of contrail formation areas is crucial to preserve tactical surprise and improve survivability of military aircraft. [Peters, 1991] To avoid the possibility that aircraft will be detected by their contrails, mission planners can make adjustments to flight levels or routes for a given mission based on an accurate contrail formation forecast and minimize the chances for detection, especially at critical mission points. [Peters, 1993]

The Appleman Method

In 1953, Herbert Appleman constructed curves showing the critical temperature for contrail formation as a function of pressure, relative humidity, and temperature. Figure 1 shows the results of his work.

Appleman concluded that in a dry environment contrails form at very cold temperatures, whereas in a more humid environment contrails can form at warmer temperatures. [Weaver]

Appleman used a contrail factor, defined as the ratio of moisture to heat released by the combustion of jet fuel which can be converted to a mixing ratio to temperature ratio, of 0.0336 g/kgC. The contrail factor determines the slope of the Appleman curves and can be significantly different for different types of aircraft engines. [Weaver]

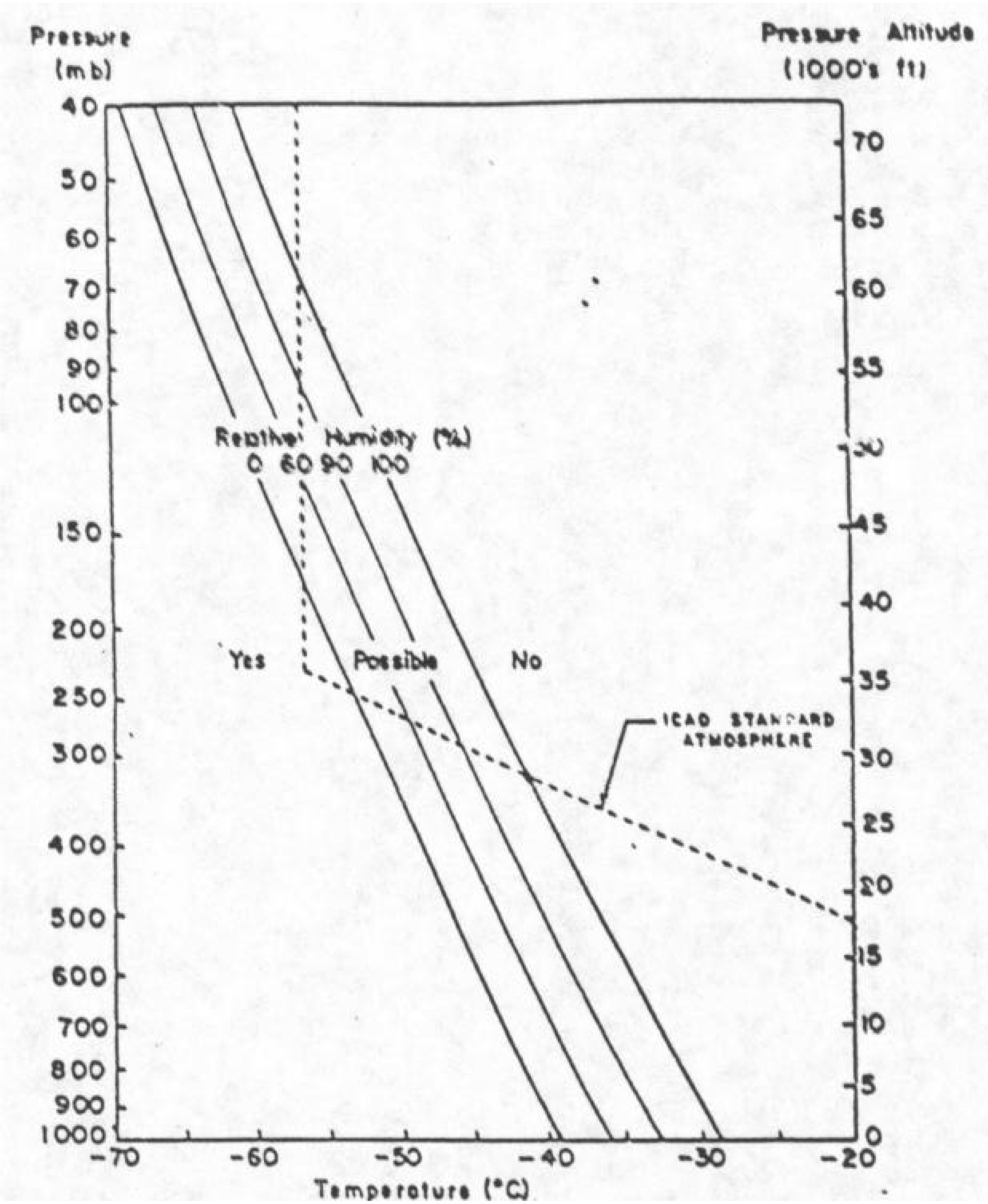

Figure 1. Contrail forecast chart. Chart uses relative humidity, temperature, and pressure to forecast contrail formation. (After Appleman, 1953).

The biggest limitation in using the Appleman curves is that both temperature and moisture data are needed. Unfortunately, accurate moisture data are still not available from CONUS upper air sites. [Weaver]

Prior to 1 June 1995, Air Force Global Weather Central (AFGWC), now the Air Force Weather Agency (AFWA), produced contrail forecasts based exclusively on Appleman’s work. [Shull, 1998]

Today, the original Appleman technique forms the basis of the AFWA’s contrail forecasting algorithm. [Schrader, 1997]

Improvements to the Appleman Method

In a study by the Strategic Air Command, contrail forecast techniques based on the Appleman curves predicted 24 percent of contrail occurrences and 98% of non-occurrences. A more reliable technique to forecast contrail occurrences was critically needed to support strategic flight operations. Using updated temperature and synoptic-scale vertical motion sensitivities of contrail formation, a 65 percent verification of occurrences and 86 percent verification of non-occurrences was achieved. The following rules were identified:

1. If $T \leq -50℃$: Forecast contrails.
2. If $-49℃ \leq T \leq -40℃$ and there is upward motion: Forecast contrails.
3. If $-49℃ \leq T \leq -40℃$ and there is downward motion: Forecast no contrails.
4. If $T \geq -39℃$: Forecast no contrails.

These results clearly indicate that vertical motion is an important factor to consider when forecasting contrails, especially in the absence of accurate relative humidity observations or forecast. [Peters, 1991]

When making forecasts of contrail formation, one must use a representative value for the contrail factor of the engine type under consideration. [Schrader, 1997] A single contrail factor does not suitably describe this ratio for all types of engines. [Shull, 1998] New contrail forecast algorithms for the three most common engine categories (non-bypass turbojet (.0360 g/kgC), low-bypass turbofan (.0400 g/kgC), and high-bypass turbofan (.0490 g/kgC)) have been in operational use since 1 June 1995. Figures are available similar to Figure 1 for each different engine type. The result is a significantly different critical temperature for each of the three engine types. In all cases, the new, easy to use algorithms showed better forecast skill than the Appleman method. [Peters, 1993] This method remains the best for operational contrail forecasting. [Schrader, 1997]

The most recent change to the AFWA JETRAX contrail forecast model was 13 January 1997. AFWA switched to the Navy Operational Global Atmospheric Prediction System (NOGAPS) global spectral forecast model as a source of its initial data. In a recent study, JETRAX is providing excellent contrail forecast products. It has an overall Hit Rate of 84.4 percent and a False Alarm Rate of 15.2 percent. The 30-hour forecasts are providing mission planners with information that is more than 80 percent accurate, while forecasters are briefing pilots with an 18-hour forecast that is nearly 90 percent accurate. [Shull, 1998]

Atmospheric Conditions Favorable for Contrail Formation

Jiusto and Pilie, 1964, found that contrails occurred in the immediate tropopause region (within 2000 ft), regions of cirrus, on the right side of jet streams (within 400 miles of the jet axis) looking downstream, and in the vicinity of upper-level low pressure cells. They also determined that contrails were unlikely on the left side of the jet stream (100-300 miles from the axis) looking downstream and in areas where cirrus clouds were absent. The formation of contrails then is closely related to cirrus. If temperature and humidity conditions are favorable for cirrus, they are very probably favorable for contrails, though the inverse is not so probable because contrails can occur with zero humidity if the temperature is cold enough.

The combination of cold temperatures and high relative humidity makes the immediate tropopause region generally favorable for contrail formation. Aircrews hoping to elude detection from ground observers should routinely avoid the tropopause level. [Weaver]

Since contrail formation is so closely linked to cirrus clouds, if we can forecast cirrus clouds we can forecast contrail formation. Cirrus clouds are normally associated with fronts, thunderstorms, and jet streams; however, these clouds are difficult to observe and forecast. A key limitation in cirrus forecasting, like contrail forecasting, is the lack of reliable humidity data at upper levels. Contrail formation then is closely related to areas of upper-level moisture, cirrus clouds, jet streams, and areas of upward motion ahead of upper-level troughs. [Weaver]

Contrail persistence, like formation, depends on the relative humidity. Whether contrails persist or not depends on if the atmosphere is saturated with respect to ice. Contrails will persist if the atmosphere is supersaturated with respect to ice. Synoptically, there appears to be a well-defined relationship between trough-ridge patterns aloft (300mb) and contrails. These areas are generally favorable for contrail formation:

1. Low pressure areas in the upper troposphere and high pressure areas in the lower stratosphere.
2. The entire 200 mb level in winter. At 100 mb, south of 45°N in summer, south of 40°N and north of 60°N in winter.
3. North of 35°N in winter and north of 60°N in summer at 300 mb.
4. On the right side of jet streams looking downstream, up to about 400 miles from the axis.
5. The tropopause level plus or minus about 2000 feet.
6. Areas of positive vorticity advection at 300 mb or where cirrus clouds are present.

Future Improvements

Because the contrail forecasting process uses assumed, rather than actual, relative humidities, accuracy is still limited. To refine contrail forecasts further, accurate observations and forecasts of relative humidity are needed well into the stratosphere.

Another limitation is the possibility that the new algorithms may not meet specific user requirements because of different engine exhaust characteristics. [Peters, 1993]

Earlier forecast techniques proved satisfactory predicting contrails in relatively moist conditions. However, it was noted that forecast quality diminished drastically in dry environments. With the United States' continuing involvement in air operations over the Middle East, the need for an accurate dry environment contrail forecast algorithm has taken on new importance. [Asbury, 1997]

Conclusion

Early forecast methods by Appleman provide the groundwork for today's complex contrail forecast algorithms. Modifications to Appleman's original work to include factors such as aircraft engine type and synoptic-scale vertical motion provide significant improvements to forecast skill. Combining the output from a contrail forecast algorithm for the particular aircraft engine characteristics with the first-hand knowledge of the synoptic weather patterns over the flight path, a forecaster can provide a very accurate forecast for contrails. There is little dispute that contrails have a significant impact on military missions. Accurate contrail forecasts help mission planners and pilots avoid the levels where contrails form. Mission effectiveness is thereby enhanced. [Shull 1998]

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